Hydrocyclone Modelling

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1 Introduction

A key part in the development of our filtration system was predictive modelling. Our filtration system initially looked to include a hydrocyclone, to separate the microplastics and a small percentage of the water from the main body of liquid and particulates being ejected from household washing machines. Our aim was to use a hydrocyclone to reduce the flow rate of water entering our filter whilst still retaining the microplastics we needed to degrade. Our model was used to predict the dimensions of a hydrocyclone that would need to be attached to the back of a household washing machine to separate the microplastics from the main body of fluid.

2 Hydrocyclone background

Hydrocyclones are a cono-cylindrical shape, with a tangential feed inlet into the cylindrical section and an outlet at each axis [1]. Figure 1 details the key features of a hydrocyclone that are essential to its function. Hydrocyclones are operated vertically, with a spigot at the lower end. The fluid enters in through the inlet creating a tangential flow into the main body. This, in turn, produces a vortex effect in the central compartment of the cyclone, where the more dense particles circulate at high velocity around the outer edge of the chamber and create an underflow that leaves through the spigot. The less dense particulates, due to the small area of the spigot, create an inner vortex that then travels in the opposite direction but upwards through the centre of the cyclone [1].

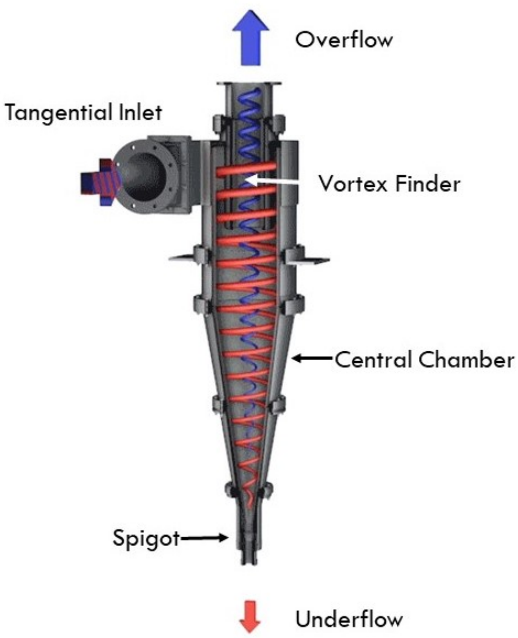

Figure 1: Labelled diagram of a hydrocyclone, detailing the key features. [2]

The main industrial purpose of a hydrocyclone is for the de-watering of slurries, which is defined as a mixture of solids with a specific gravity greater than 1 suspended in liquid [3]. Some types of commonly used slurries are soil slurry, coal slurry and cement slurry; a mixture of water and a selection of dry or liquid additives.

With hydrocyclones being widely used in industry and tolerating very high flow rates [4], we believed they would be ideal for our purpose and potentially for the scale up of our filter. They can also be used in series or parallel with each other to increase the efficiency of the separation process.

3 Methodology

3.1 Requirements for our model

In our model we used a research paper intended for other engineers which focused on the analysis and development of hydrocyclones systems for function in grinding mills [5]. This model for hydrocyclones allowed us to see the general design principles, from the dimensional analysis to allowable flow rates and corrections to the design. We therefore used this mathematical method to produce a model for our own hydrocyclone for a household washing machine.

To analyse our own application for microplastic removal we required this data:

1. The fluid flow rate entering into the tangential inlet
2. The % weight of solid particulates in the inlet fluid
3. The % of fluid desired in the overflow
4. The smallest diameter of the particulates that need to be filtered after the overflow has left the hydrocyclone
5. The specific gravity of the particulates and the fluid containing them

3.2 Assumptions

For this model several assumptions had to be made. As the field of microplastics is relatively new, especially it's application within industry, logical assumptions had to be made to develop this model. The minimum size of the microplastics was assumed based upon research done at Plymouth University [6]. There has also been an assumption that the smallest value will be a single fibre's face diameter, as during the washing process fibres can sometimes clump together. The pressure drop in the hydrocyclone has been chosen as the most economical value from a manufacturing and maintenance perspective.

3.3 Microplastics and Washing Machine: Test and Research Data

To model our hydrocyclone successfully we needed to use real data taken from tests with our own washing machine in the fluids laboratory, and data from the Plymouth University [6] experiments regarding the size and shape of microplastic fibres.

One of the requirements for modelling the geometry of a hydrocyclone is the % weight of the solid particulates in the inlet fluid i.e. the outlet fluid from the washing machine. Therefore, we needed to run tests to determine the flow rate of fluid leaving the washing machine.

Protocol:

1. Determine appropriate settings for the washing machine cycle: 1400 spin, 40 degrees and short wash (124 minute cycle)
2. Weigh out clothes made from polyester fibres and cotton fibres to represent a standard home wash in kg intervals up to the desired weight
3. Wash with the same volume of detergent for each load to ensure repeatability
4. Attach a flow meter to the outlet tubing of the washing machine
5. Monitor the outflow tubing and flow rate meter, making note of the outflow release time in the cycle, the maximum flow rate in litres/min of each release
6. Once the wash is completed, check the flow rate meter for the total amount of fluid released in litres

To find the % weight of solids within the number of litres that is ejected from the washing machine, we needed to use the Plymouth data [6] that states the minimum and maximum size of a microplastic fibre. This meant we could calculate the mean volume of a fibre leaving a standard wash.

Plymouth states that an estimated number of 728,789 fibres leave a standard 6kg wash [6], therefore making it possible for us to calculate the total weight of microplastic fibres using our own fluid data. A 6kg wash from our experiment released 55.4 litres of fluid.

Table 1 shows how we calculated the % weight of fibres in a 6kg wash, therefore satisfying one of the requirements for our model.

Microplastic fibre	Diameter (µm)	Length (mm)	Volume (mm^{-3})	Mass (ng)
Minimum	11.9	5.0	1.39×10^{-4}	192
Maximum	17.7	7.8	4.80×10^{-4}	662
Average	14.8	6.4	2.75×10^{-4}	427

Table 1: Calculations using the Plymouth data, to calculate the mean weight and size of a microplastic fibre. [6]

To calculate the mass of each fibre, the density of PET plastics (1380kg/m^3) was multiplied by the average volume of a single microfibre which was calculated from the Plymouth data.

$$\text{Average mass of single microplastic fibre} = 1380\text{kg}/m^3 \cdot 2.75\text{x}10^{-15}m^{-3} = 427\text{ng} \tag{1}$$

The mass of a single fibre was then multiplied by the number of fibres released from a 6kg wash, 728,789 to get a total weight of microplastic fibres released in the wash as 0.311 grams. Furthermore, the total number of kg of fluid released from a 6kg wash was 55.4kg. To find the % of microplastics by weight within this fluid, 0.311grams was divided by 55.4kg, in equivalent units.

$$\%\text{ of microplastics released by weight} = \frac{3.11\text{x}10^{-4}\text{kg}}{55.4\text{kg}} \cdot 100 = 0.0006\% \tag{2}$$

Moreover, the maximum flow rate for each wash was determined in our experiments, giving the maximum value of 15.4 litres/minute, no matter the weight of the wash.

3.4 Hydrocyclone Calculations

The specific gravity of the PET plastic is the only requirement that needed to be calculated beforehand, using this formula;

$$SG = \frac{\rho_{material}}{\rho_{water}} \tag{3}$$

The density of PET plastic has a known value of 1380kg/m^3, and the density of water is 997kg/m^3 which can both be substituted into equation (1). This gives the specific gravity of PET as 1.38.

The smallest diameter of the microfibres that we considered in our model, was the smallest pore size of a filter that could be included in the final filter design. A 10 micron filter was the smallest filter used during the design and testing of our filtration system, therefore in this model 10 microns is the smallest diameter of the PET microplastic fibres.

From the previous calculations, the feed of fluid entering into the hydrocyclone includes 0.0006% microplastics by weight. As the basis of a hydrocyclone is to remove the smaller solids, i.e. the microplastic fibres, into the overflow for them to then be filtered, we wanted all 0.0006% of the microplastics to be taken into the overflow. Therefore the % of water in the overflow is 99.9994%.

Feed Inflow	
Percentage of Solids (%)	0.0006
Percentage of Water (%)	99.9994
Flow rate (litres/second)	0.25
Specific Gravity of inflow	1.00
Smallest solid particulate diameter (microns)	10

Table 2: The necessary breakdown of the fluid inlet into the hydrocyclone, including constants.

With these three requirements either calculated or assumed, the geometry of the hydrocyclone for our washing machine filtration system could be modelled. Table 2 shows a breakdown of the inlet fluid from the washing machine into the hydrocyclone.

A key part of a hydrocyclone geometry is the D50 point. The D50 point determines at which point 50% of the solids go into the overflow and 50% go into the underflow. There is a relationship between the required % of water passing into the overflow, a multiplier and the D50 point. This multiplier is used to calculate the D50C, which is the micron size that the cyclone can achieve separation for under the conditions of smallest micron passing size, the % of water passing and the associated multiplier. The multiplier to percentage passing relationship can be found in Table 3.

Percentage Passing (%)	Associated Multiplier
98.8	0.54
95	0.73
90	0.91
80	1.25
70	1.67
60	2.08
50	2.78

Table 3: The associated multiplier with the percentage of solids passing into the overflow

The percentage of microplastics intended to pass into the overflow are 98.8% as they are the only contaminants we want to remove from the water and it is important we remove almost 100%. Therefore, the associated multiplier is 0.54. Using this information the D50C can be calculated using the following formula;

$$D50C(\text{application}) = \text{micron size for application} \cdot \text{multiplier} \tag{4}$$

$$D50C(\text{application}) = 10\text{microns} \cdot 0.54 \tag{5}$$

After calculations the D50C(application) is 5.4 microns for active application. This is the minimum micron size that this cyclone could separate into the overflow. This value will be later used to calculate the diameter of the cyclone. A number of factors can affect the performance of a hydrocyclone, including a) the influence of the concentration of solids contained in the feed fluid, b) the pressure drop across the cyclone and c) the effect of the specific gravity that the liquids and the solids have on the separation. There are associated corrections for each of these effects which were calculated.

3.5 Correction 1

Correction one accounts for the concentration of the solids by volume in the feed fluid, this is crucial as it considers the viscosity of the solids as they pass through into the cyclone. Where V is the percentage solids by volume of cyclone feed, correction 1 is calculated using;

$$C1 = \left(\frac{53 - V}{53}\right)^{-1.43} \tag{6}$$

In our case V is also 0.0006%. Substituting this value into the formula gives the first correction as 1.0000

3.6 Correction 2

Correction two accounts for the pressure drop across the cyclone, which is the difference in pressure between the inlet feed and the outflow. Standard cyclones have an outflow pressure of 101kPa, atmospheric pressure. The pressure of the inflow is usually determined by the requirements for maintenance and efficiency reasons. The recommended pressure drop is 50kPa in the inlet feed, therefore this is the value to be used in the correction calculation as shown below, where δ P is the pressure drop in kPa;

$$C2 = (3.27 \cdot \delta P)^{-0.28} \tag{7}$$

This formula gives the second correction as 1.0647.

3.7 Correction 3

The final correction, correction three, is the effect the specific gravity of the solids and the liquids within the flow have on the separation. The SG of PET is 1.38 and the SG of water is 1, suggesting that they are similar in density. The calculation of this correction uses the formula below;

$$C3 = (\frac{1.65}{GS - GL})^{0.5} \tag{8}$$

Where GS is the specific gravity of the solid and GL is the specific gravity of the liquid. Using our own values, correction three is found to be 2.0800.

Table 4 shows the three calculated corrections to the feed.

Correction	Value
1	1.0000
2	1.0647
3	2.0800

Table 4: The three corrections C1, C2 and C3 to the feed into the cyclone.

3.8 Final Calculations for Cyclone Geometry

With these three corrections, and the D50C(application) calculated earlier, the D50C(base) can be found. The D50C(base) is needed to find the cyclones diameter. Using the following formula;

For the calculation of D50C(base):

$$D50C(\text{application}) = D50C(\text{base}) \cdot C1 \cdot C2 \cdot C3 \tag{9}$$

For the diameter, D:

$$D50C(\text{base}) = 2.84 \cdot D^{0.66} \tag{10}$$

C1, C2, C3 and the D50C(application) are used to find D50(base) with a given value of 2.44 microns. The D50C(base) is then used to find the diameter, which has a given value of 0.76cm.

Therefore the cyclone, based on standard cyclone geometries, will have the dimensions as shown in Figure 2. The dimension are determined from the diameter, based on a set of standard proportions for a hydrocyclone. For example, the inlet nozzle should be 0.05 multiplied by the diameter squared, the apex orifice can be anywhere between 10% and 35% of the diameter and the cylindrical chamber should be 100% of the diameter.

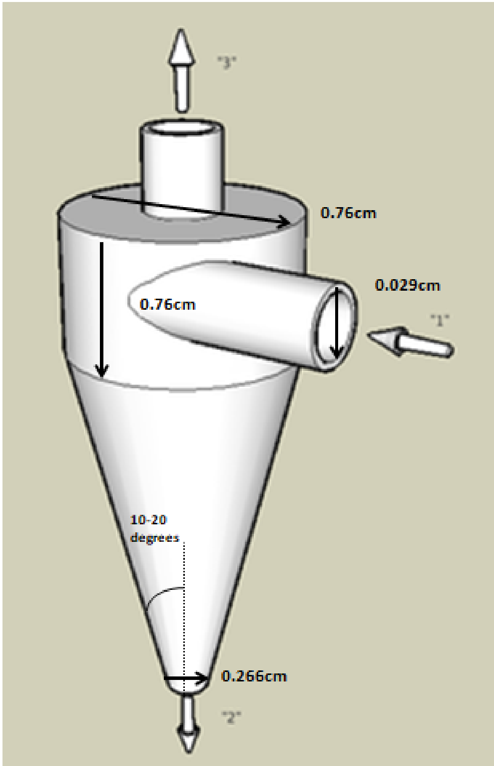

Figure 2: A diagram of a hydrocyclone, annotated with our calculated values [7]

4 Conclusion

This modelling has given our team an insight into the use of a hydrocyclone in our filtration system. As the hydrocyclone would need a diameter of 0.76cm to remove 98% of microplastics from water, this is too small to even consider being part of the filtration device. This size requirement for a hydrocyclone wouldn't be able to withstand the flow rate released from a standard household washing machine. Our team has speculated that this is due to the % of microplastics being 0.0006% of the total weight leaving the washing machine in a standard cycle. Industrial hydrocyclones have 60% of the inlet feed being solids and 40% being water, as opposed to our 0.0006% and 99.9994%. We further considered whether hydrocyclones could be used within larger industry for example, at mills or water treatment plants. However, as most of the microplastics in the water system and the fashion industry come from the washing process, just on a larger scale, the ratio of microplastic fibres to water would not change enough for a hydrocyclone to be effective.

However, it is important to realise that as it is very difficult to test for some of this data used, the values used in this model have been taken from a wide range of sources and research groups who may all use different test methods. Therefore, the continuity of the data used in this model, should quite reasonably, be speculated and considered carefully.

Based on our own final results, the team concluded that due to the nature of microplastic release from washing machines, a hydrocyclone is not suitable for this purpose. This has informed our research, so that we can look closely into the most effective filtration system without a hydrocyclone. As the purpose of a hydrocyclone in this system was to reduce the water flow into the filtration system we will need to change and adapt our filter so that it can withstand 15.4 litres/min of fluid at any point.

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